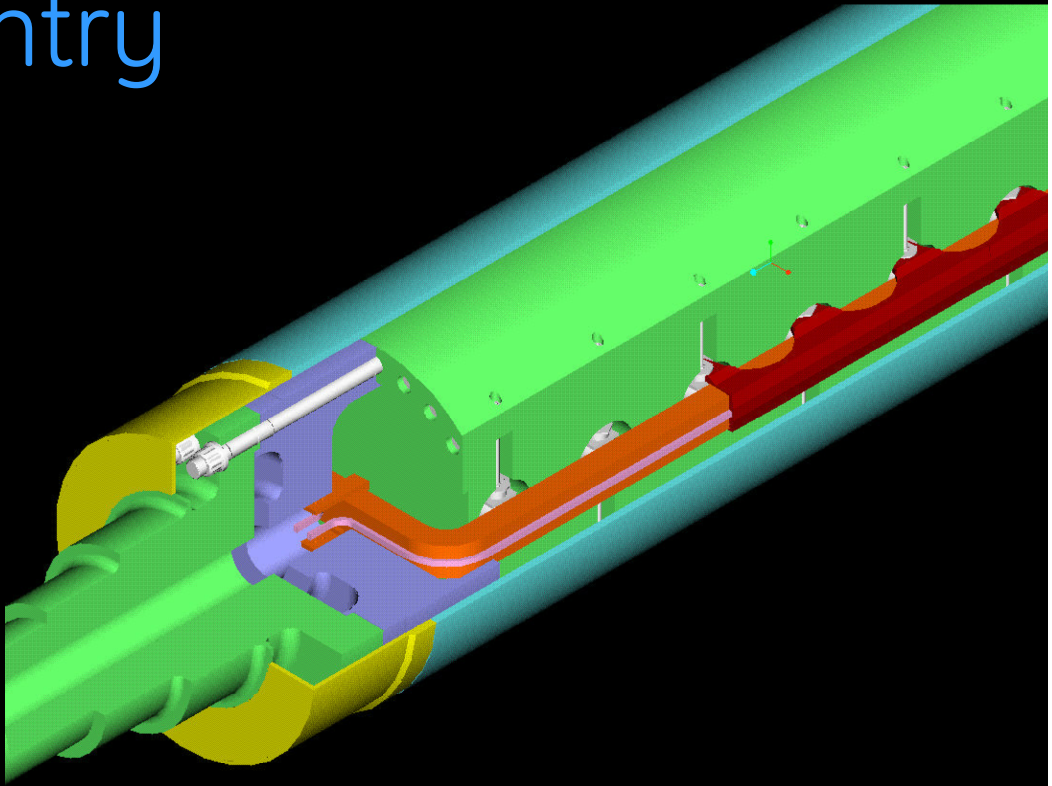
Design and Development of a 100MVA Generator for Commercial Entry

Agenda
Help
Summary



Jim Fogarty

DOE Peer Review,
Washington, DC
August 2 - 4, 2005

imagination at work

Key Program Objective

Build and test a full-size 100 MVA HTS generator

We succeed if…

- We maximize efficiency benefit
- It is cost competitive
- It is reliable as conventional equipment

Maintain or improve reliability…

…Financial value to purchaser

HTS Generator Team and Major Vendors

GE - Global Research

- HTS & cryogenic technology

GE - Power Generation

- Generator technology

GE - Energy Consulting

- Grid interaction studies

American Electric Power

- Perform power plant integration analysis
- Analyze commercial benefits
- Evaluate impact on T&D

ORNL

- Emissivity
- Insulation characterization
- Quench & stability

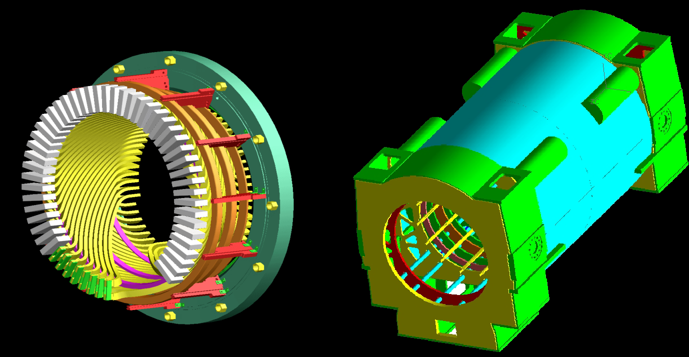
LANL

- AC losses
- Vacuum maintenance
- Passive cryogenic pumping
- Heat pipe cooling
- Gen 2 wire evaluation

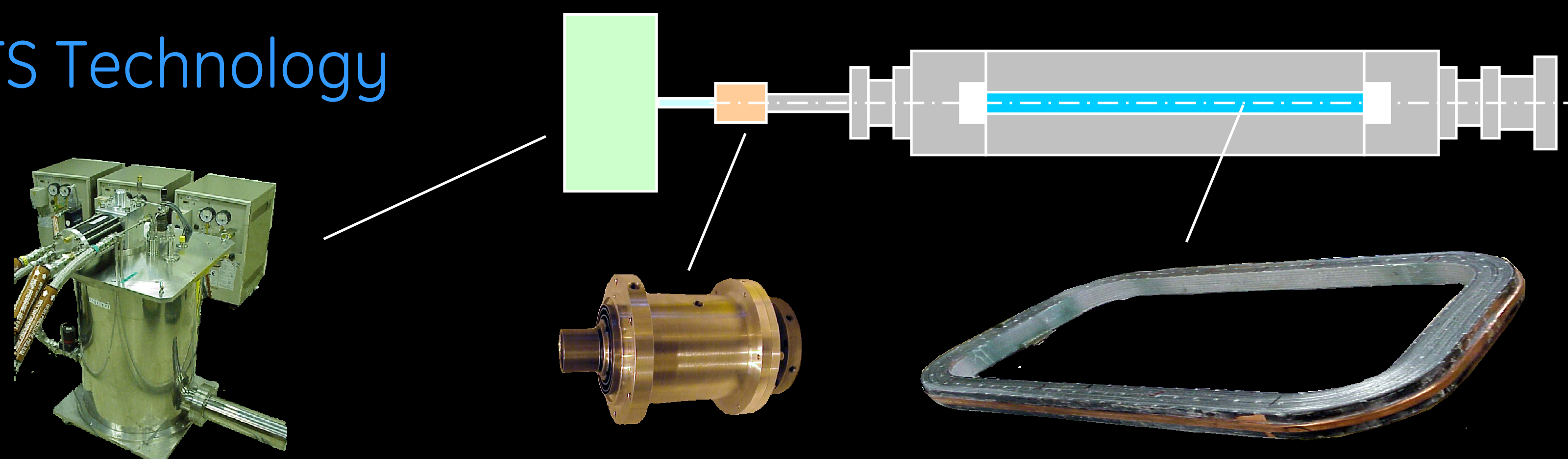
100 MVA HTS Generator Configuration

Keep Conventional Technology

- Stator Core and Winding
- Frame and Coolers
- Exciter
- Rotor Forging



Add HTS Technology

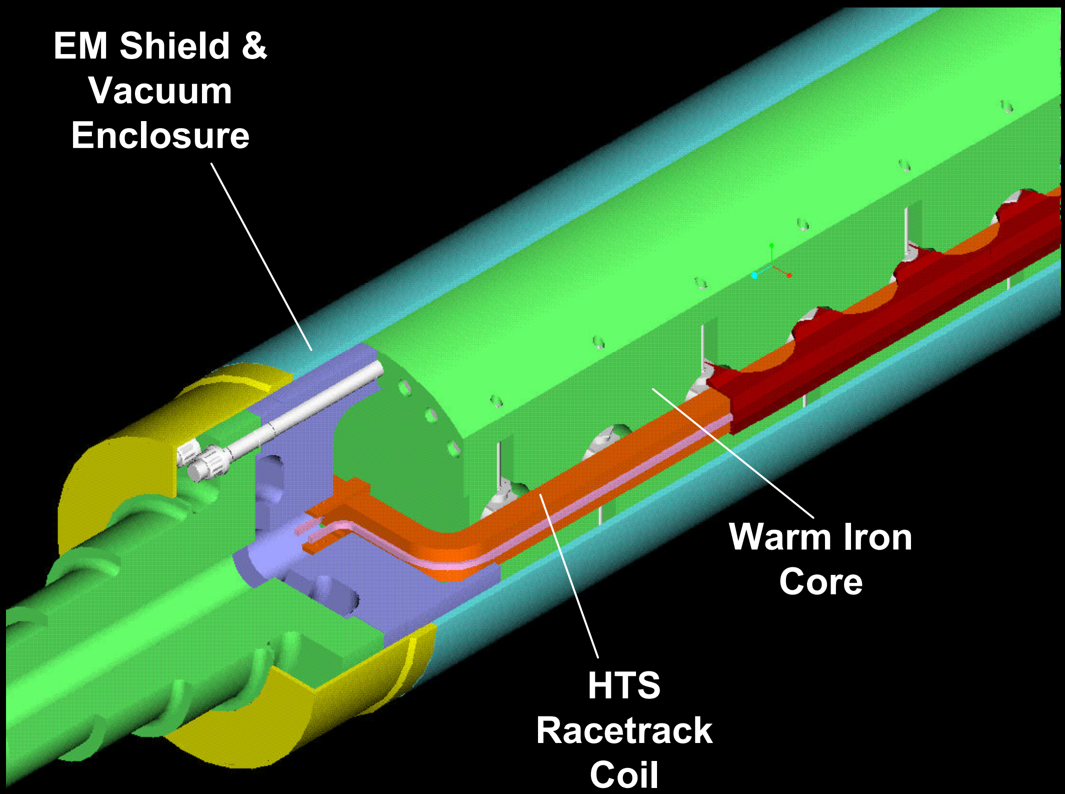


Refrigeration System

Cryogen Transfer Coupling

HTS Field Coil

GE's Warm Iron HTS Generator



- Machine torque acts on the iron
- Minimal cold mass
- Minimal HTS wire
- Simple gaseous He cooling
- No changes to balance of generator

"Plug Compatible" with a Gen 2 HTS coil

The Value of Efficiency

Assume

- $5/MM BTU fuel cost & $35/MW-hr electricity price
- 15 year time window
- 250 MW net output
- 8000 hr base loaded unit
- 60% combine-cycle efficiency
- Shift in generator efficiency from 99 to 99.5%
- 15% return on investments

Constant 250 MW output

- $273K/yr fuel savings
- $1.84 MM NPV

Sell the saved energy

- $353K/yr added revenue
- $2.37 MM NPV

Caveat: Efficiency benefit maximum for base loaded units – usually more than 250 MW

Reliability & Availability

"No thermal cycling"

- Cool down at startup
- Rotor stays cold – either in stator or on turbine deck

On-line maintenance of cryocooler

Field coil insulation

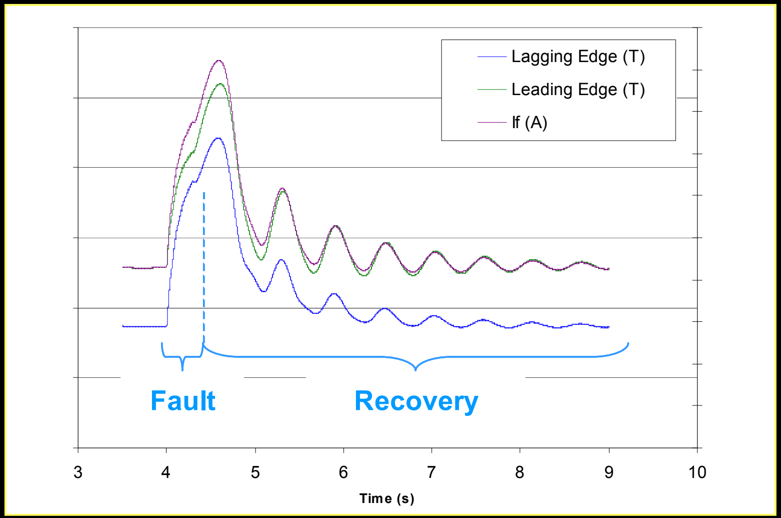
- 10:1 reduction in coil surface area
- Minimize risk of field coil ground
- Fully bonded coil – eliminate turn-turn shorts

Commercially proven excitation system

The HTS Generator on the Power Grid

Generator characteristics

- Higher short circuit ratio
- Comparable subtransient reactance
- Improved unbalanced current capability (I_2^2t)



Exciter characteristics

- Commercial EX2100 exciter
- Enhanced PSS
- Permissives & protection for HTS systems (quench etc.)

Recovery following fault on HV side of step-up transformer

Technology Barriers to Commercial Success

HTS wire + refrigeration is too expensive…

"Where is Gen 2 wire cost headed… and when?"

Refrigeration costs

- GM's
- Reverse Brayton?
- Pulse Tube?

GE has no direct control…

We will state our needs…

HTS Wire Properties

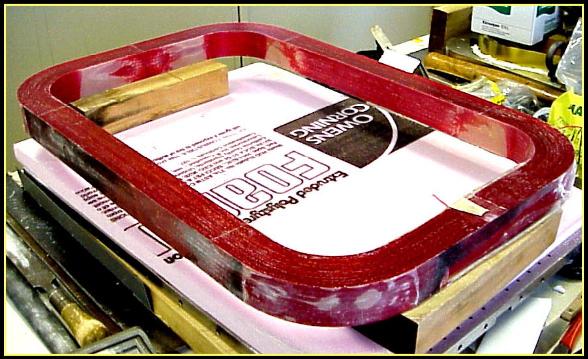
- Must have higher strain capability
- 125 A wire @ 50K & higher, 2 – 3 T field

Quench Investigations

Objectives

- Investigate local & global heating behavior
- Overcurrent capability
- Obtain signals useful for quench prediction

Results



- Tests in Nov 04 & Mar 05
- Long term operation above I_c
- Useful electrical & thermal signals
- Numerous coil quenches
- Last quench damaged coil
  - Weakness in current lead area
  - Alternative configuration being implemented

Coil Support Retest

2002 1.5 MW demonstrator test

- Verifies coil & rotor dynamics
- Uncovers weakness in coil support

New approach

- Based on advanced rotor dynamics analysis
- Original 1.5 MW rotor rebuilt & mechanically retested
- Predictions verified and factored into present coil support

Coil support reviewed with DOE – July 05

2005 GE Accomplishments

- Refrigerator on order
  - Air Liquide Helial 1000
  - Delivery in 2005
- Coil bobbin on order
- Wire being insulated
- Quench detection tests
- Finalized coil design & support
- Exciter – HTS coil interaction analyzed
- Readiness Reviews
  - HTS Coil
  - HTS Coil Support
  - EM Shield/Vacuum Enclosure

Air Liquide Helial 1000 Cryocooler

2005 LANL & ORNL Accomplishments

ORNL

- Emissivity variation with surface contamination
- Quench detection & prediction – at GE-Global Research
- Dielectric tests on surrogate coils (linked with LANL)

LANL

- Outgassing behavior of materials
- Application of heat pipes to HTS coil cooling
- Transient behavior of reverse-Brayton cooling system
- AC losses/overcurrent behavior
- 2G wire investigation

Details to follow…

2006 Plans

Complete detailed design (Design Review 3Q06)

Complete full scale HTS coil

- Electrical tests
- Cool-down tests
- Critical current measurement

Perform cryocooler acceptance tests

Order long lead materials

- Shaft forging
- EM shield
- Excitation system

Major milestones

Conceptual Design	Complete
Preliminary Design	Preliminary Design Review to be held FW 39
Coil Winding & Coil Support	Coil bobbin on order Full scale wind trial 4Q05
Refrigeration System	Delivery 4Q05 Acceptance test 1Q06

Overall Schedule

Preliminary Design Review	Sept 2005
Detailed Design Review	3Q2006
Rotor Fabrication	2007
Factory Tests	First half, 2008

High Temperature Superconducting Generator

2005 Annual Peer Review

Superconductivity Program
for Electric Systems
U.S. Department of Energy

August 2-4, 2005
Washington, DC

Project Objective

- **Project level goal:** Support the successful demonstration of 100 MVA generator HTS rotor retrofit

Areas of Emphasis

- **Emissivity** –Assessment of radiation heat load to HTS rotor coil
- **Quench and Stability** – Characterization of HTS prototype coils in order to predict coil performance during and after transients and overload conditions
- **Dielectrics** – Performance of coil winding when voltages are applied during normal operation of the coil and from changes in the operating conditions of the rotor

FY 2005 Milestones

- Expand emissivity investigation to observe whether other plated materials degrade similarly due to water and air contamination
- Refine measurement of emissivity degradation due to indirect contamination from outgassing
- Provide multiparameter curve fit for $R(T,I,I_c(B))$ to use in over-current simulations of generator
- Test dielectric insulations for partial discharge and advanced aging curves at 77 K and 25 K
- Test layer-to-layer insulation for impulse breakdown, PD, and pulsed aging
- Build prototype coils with preferred insulation and test partial discharge, impulse breakdown, and advanced aging

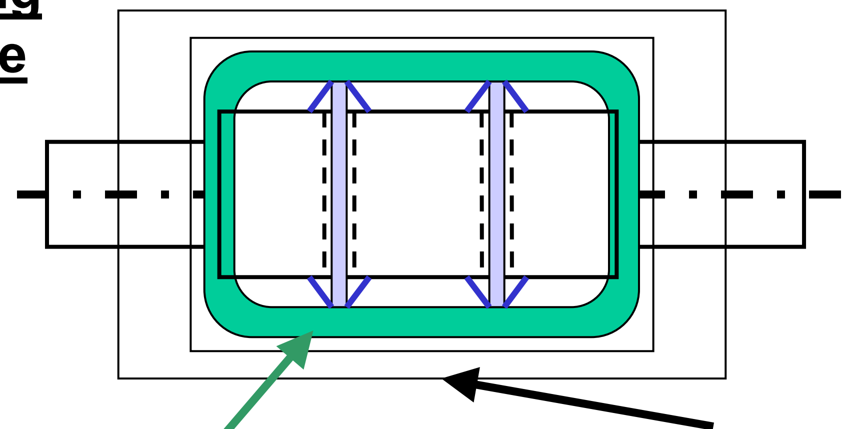
FY 2005 Results

- **Emissivity**
  - Characterized the emissivity at 30 K for several silver plated copper surfaces with different room temperature emissivities
  - Examined emissivity degradation effects due to direct water and air contamination.
  - Incorporated the outgassing of rotor structural components to provide relevant indirect contamination for emissivity degradation studies
- **Quench and Stability**
  - Reviewed quench protection scheme for 100 MVA generator in noisy backgrounds.
  - Worked with GE staff on quench and stability testing and analysis of demonstrator rotor coils
- **Dielectric testing**
  - Examined partial discharge in trapped air-filled gaps at temperatures between 295 K and 41 K.

Low emissivity surfaces reduce thermal radiation heat transfer on the HTS generator

Emissivity

- **Motivation – Due to constraints on thermal insulation in rotating cryostats, low emissive surface needed to minimize radiation heat transfer**
- **Issues:**
  - Emissivity at 30 K
  - Degradation of emissivity due to air and water
  - Sources
    - Seal leakage (direct)
    - Outgassing of structural components of rotor (indirect)



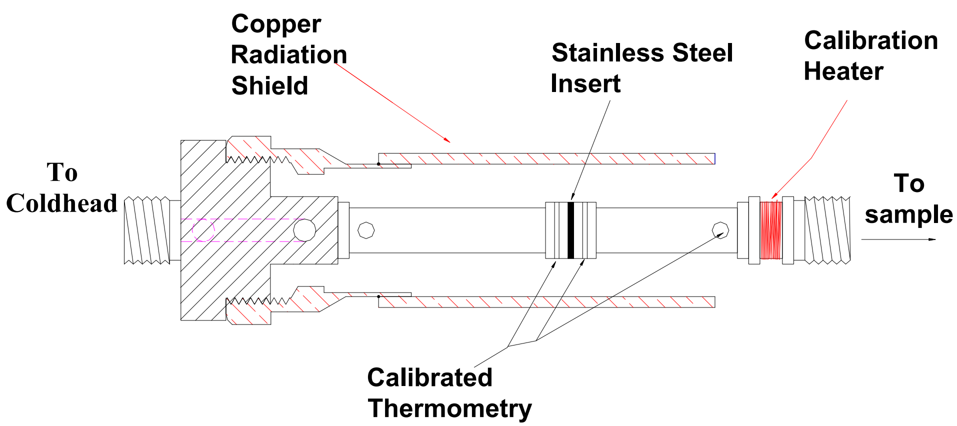
$$Q_{radiation} \propto \varepsilon$$

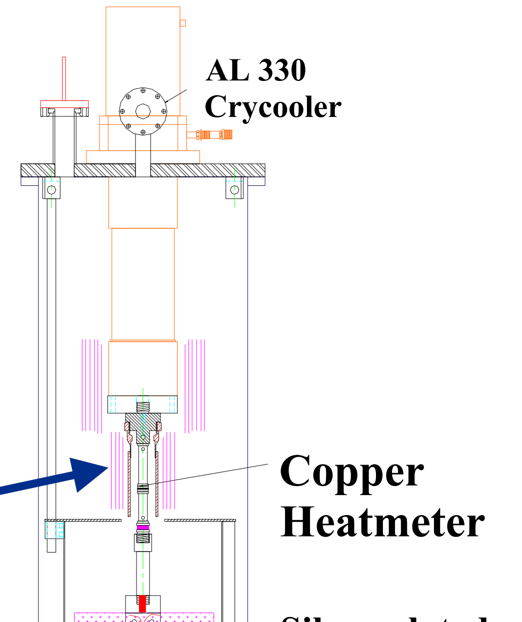
Refrigeration is one cost driver for final 100 MVA generator

Emissivity measurements test apparatus is based on energy balance of sample.

Cryogenic Experimental Setup

- Background heat load and heater w/o sample
- Radiation heat load with sample



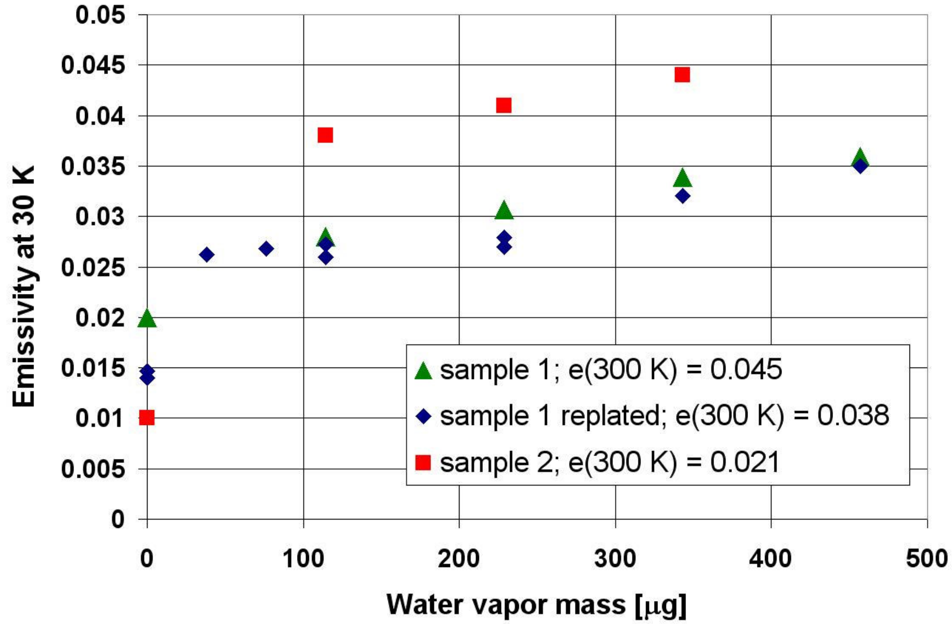


- Ag-plated copper samples
- Contaminants
  - Direct water vapor and/or air
  - Outgassing of non-metallic rotor materials

Significant change in emissivity due to direct water contamination at 30 K

- **Three samples with different values of ε(300 K) were examined.**
  - **Sample 1 - ε(300 K) = 0.045**
  - **Sample 1 replated – ε(300 K) = 0.038**
  - **Sample 2 - ε(300 K) = 0.021**

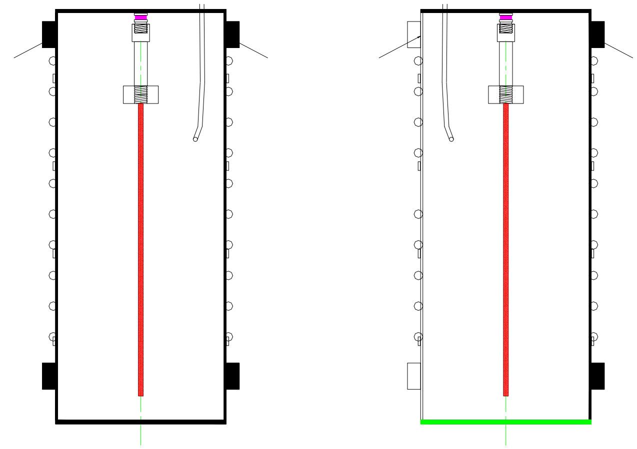
- **Repeatability of emissivity after contamination indicates that emissivity degradation is surface dominated.**

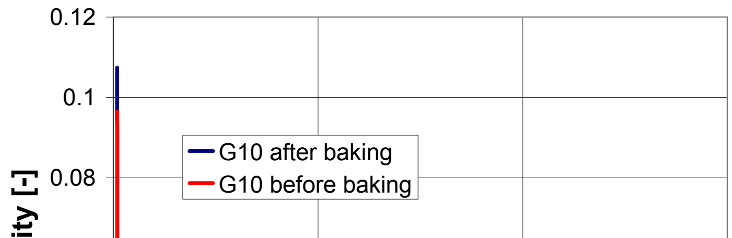


Emissivity

Outgassing of G10 component causes slight degradation of emissivity

- The bottom plate of the thermal shield was replaced with G10
- Results indicated that the outgassing rate is significantly lower than previously reported by LANL. This reduction is likely due to drop in shield temperature.
- In addition, vacuum baking G10 for one hours caused some reduction in the





Emissivity

Implication

Understanding and controlling emissivity effects and contamination sources allows the manufacturer of HTS equipment to minimize refrigeration heat loads and costs as well as the costs of contamination management in a production environment.

Partial Discharge in Air Gaps between Insulated Bi-Sr-Ca-Cu-O Tapes Degrades Electrical Insulation

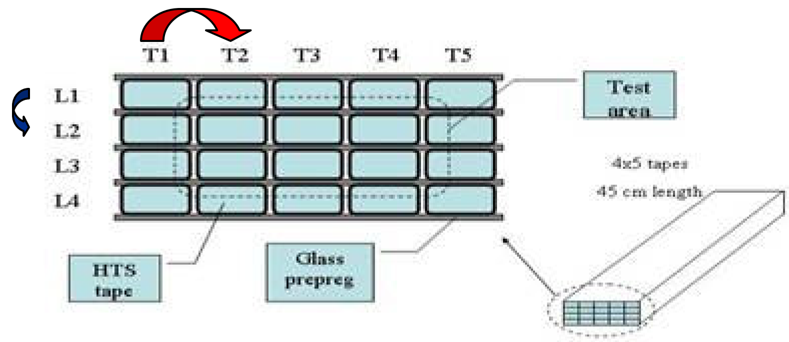
- **<u>Motivation: From previous work, partial discharge was seen as a key issue in rotor voltage dynamics.</u>**

Why is partial discharge important?

- Partial Discharge (PD) is the primary aging mechanism for cold dielectrics in HTS power applications
- PD can reduce lifetime of insulation or cause catastrophic failure
- PD can occur in embedded voids, gaps, delaminations in solid dielectrics
- PD can occur in voids under repetitive pulse applications
  - **Could occur in rotor coil because of 360 Hz operation of exciter at +/- 750 V**

Layer to layer

Turn to turn

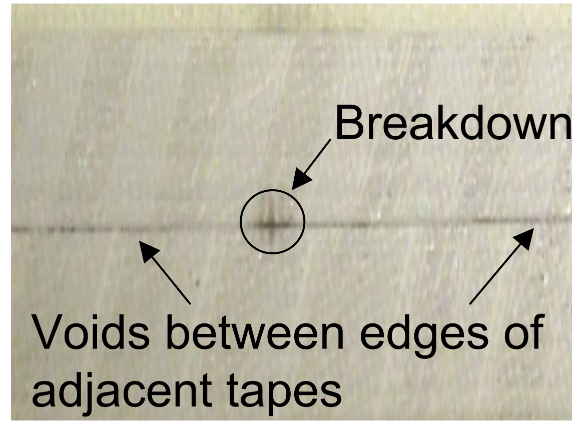


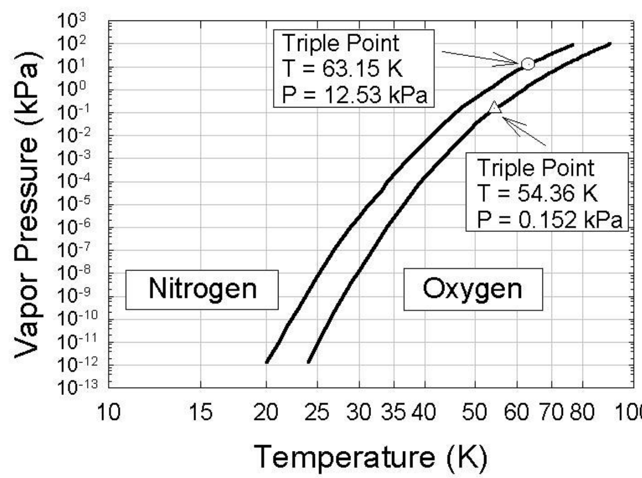
Fluoropolymer insulation wrapped on BSSCO tape

Dielectrics

Does PD onset change from 295 K to 30 K for enclosed voids?

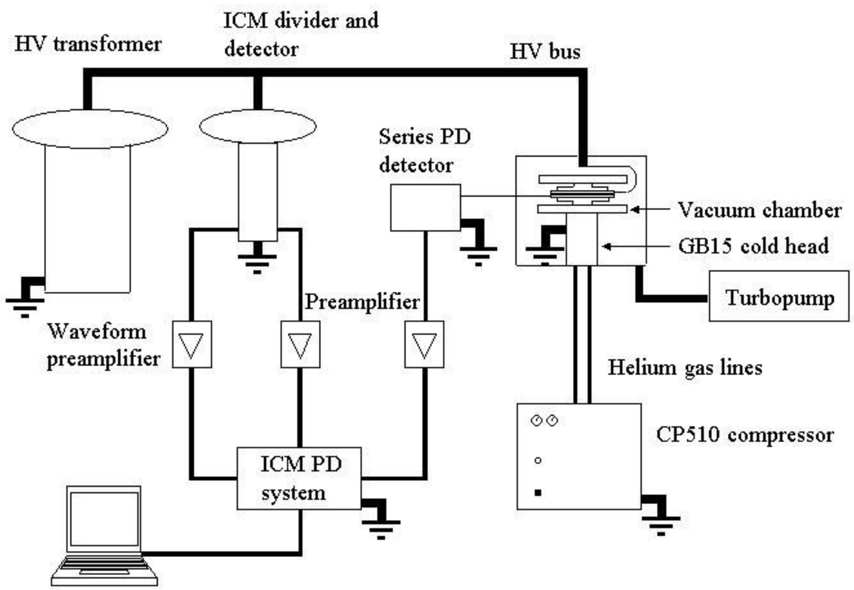
- **Gas in void may condense to liquid as temperature is lowered**
- **Below triple point ice layers may form on surface and leave vacuum in void**
- **Does PD onset increase for vacuum in void with ice layers as might be expected from Paschen's law?**
- **Experiment with cryocooler rig to measure PD vs. T**

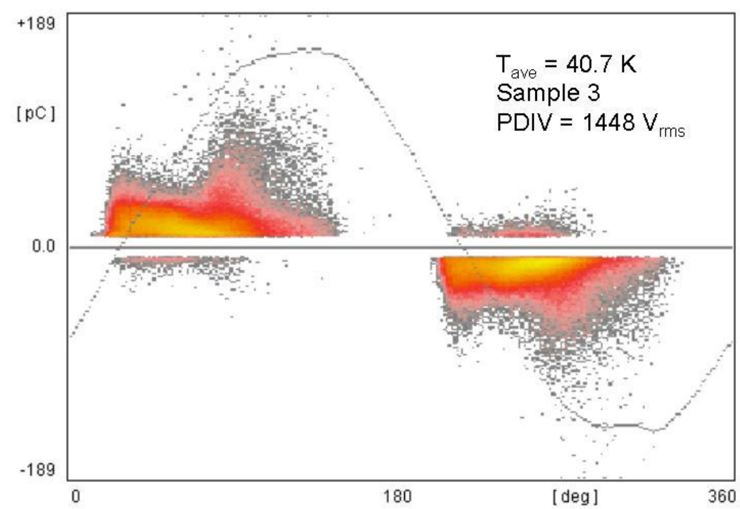




Dielectrics

PD measurements were conducted on actual HTS samples with polymer tape insulation





Phase-resolved PD pattern

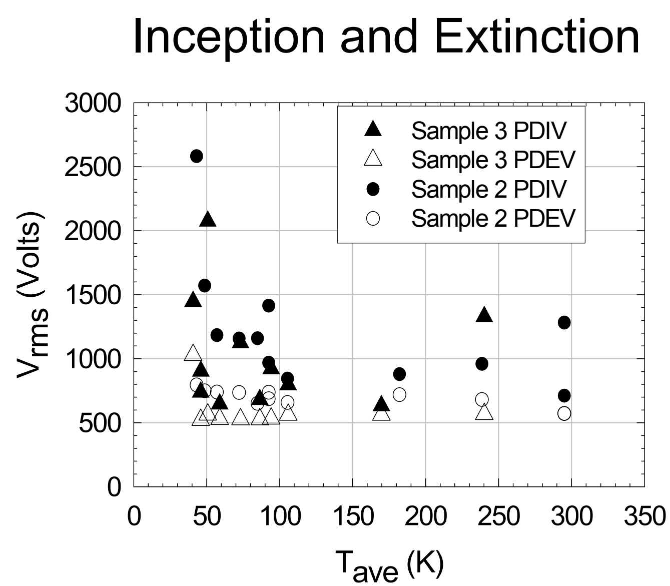
Dielectrics

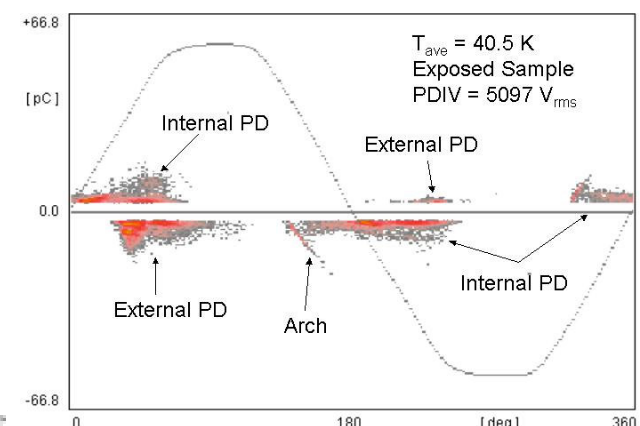
- **Tapes placed edge to edge with 1-2 mil void region**
  - **Samples cast in epoxy to trap air in void**
  - **Samples with void open to vacuum**
- **Samples mounted in cryocooler**
- **Phase-resolved digital PD detection system used**

PD onset at low T can be low – important design criteria

Conclusions

- **Gas in void condenses and/or freezes as temperature is lowered**
- **PDIV can be relatively low even at 41 K with nitrogen and oxygen "ice" layers**
- **PDIV without ice greater than with ice at 41 K**
- **Presence of ice layers may decrease PDIV over that for actual vacuum – possible desorption of gas**





With a minimum 500 V at which PD occurred, this provides a significant amount of margin given that the turn to turn voltage is a fraction of the +/- 750 V of the exciter.

Dielectrics

ORNL FY 2005 Performance

FY 2005 Plan

- Expand emissivity investigation to observe whether other plated materials degrade similarly due to water and air contamination
- Refine measurement of emissivity degradation due to indirect contamination
- Provide multiparameter curve fit for $R(T,I,I_c(B))$ to use in over-current simulations of generator

FY 2005 Performance

✓ Measured baseline emissivities of Ag-plated Cu samples at 30 K

✓ Characterized effects of direct water and air contamination on emissivity degradation of Ag-plated Cu samples

✓ Added indirect source of contamination from G10 and characterized emissivity degradation

✗ Task deleted due to demonstration of flux flow resistivity model in other coil simulations.

✓ Participated in 1.5 MVA demonstration coil quench experiments and analysis

ORNL FY 2005 Performance

FY 2005 Plan

- Test dielectric insulations for partial discharge and advanced aging curves at 77 K and 25 K
- Test layer-to-layer insulation for impulse breakdown, PD, and pulsed aging
- Build prototype coils with preferred insulation and test partial discharge, impulse breakdown, and advanced aging

FY 2005 Performance

✓ Examined partial discharge in trapped air-filled gaps at temperature between 295 K and 41 K.

✖ Task deleted due to focus on partial discharge measurements

- In progress. Test coils with surrogate conductor are being fabricated to address other rotor issues. Will take sections and run through voltage testing in late FY2005/FY2006

ORNL FY 2006 Plan

FY 2006 Plan

- Examine full scale coil with surrogate conductor with preferred insulation and test partial discharge, impulse breakdown, and advanced aging at room temperature and 77 K.
- Further develop quench detection system and test with prototype coils
- Examine integration issues of 2G tapes into rotor design and build a prototype coil to characterize.

ORNL assistance with GE Generator Risk Mitigation Issues

Area of Concern

- Uncertainty in refrigeration heat load
- Quench protection
- Characterization of HTS coil insulation

Solution

- Knowledge of emissivity degradation can lead to identification of:
  - Proper refrigeration tolerances
  - Determination of whether outgassing from non-metallic components present a long term problem
- Information on quench dynamics in prototype coils can identify the methods to detect and mitigate quenches in the 100 MVA generator
- Testing in pulsed aging, partial discharge, and impulse breakdown can lead to use of proper insulation that can sustain voltage tolerance for field installation

Research Integration

- Teleconferences with GE has lead to efficient use of resources of ORNL and GE and ensures R&D objectives, efforts, and results are in accord with project objectives
  - Exchange of information between LANL and ORNL has lead to productive discussion as to the role of materials within rotor vacuum space and their impact on vacuum quality and calculations of heat loads
- Presentations and publications during the year
  - Emissivity poster and paper to be presented at Cryogenic Engineering Conference in August 2005
  - Papers presented at the 2004 Applied Superconductivity Conference and 2004 Conference on Electrical Insulation and Dielectric Phenomena (both Oct. 2004)
- Web Sites
  - ORNL Superconductivity Web Site includes Annual Reports, Peer Review presentations and other project information
    - www.ornl.gov/HTSC/htsc.html

Design and Development of a 100 MVA HTS Generator

Los Alamos National Laboratory

Applied Engineering Tech. Group

Eric Schmierer, Todd Jankowski, Coyne Prenger, Jim Stewart, Joe Waynert

Superconducting Tech. Center

Steve Ashworth, Dean Peterson

University of New Mexico

Arsalan Razani, Dept. Mech. Eng.

2005 DOE Annual Peer Review

Washington, DC August 2-4, 2005

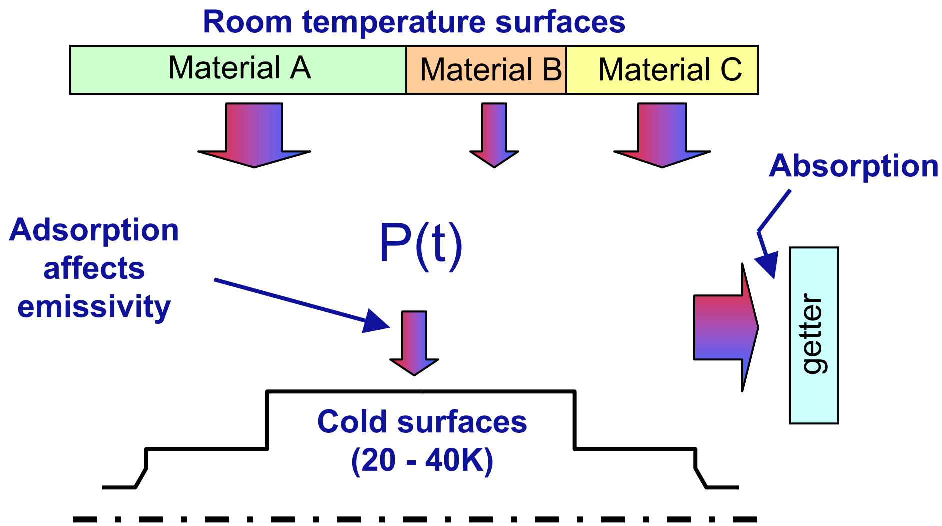
Successful demonstration of 100 MVA HTS Generator

- LANL and ORNL have entered into CRADAs with GE to provide assistance in several technology areas
- LANL technology areas
  - Long term vacuum maintenance
  - Alternative rotor cooling methods
  - Engineering support
    - AC loss characterization
    - 2nd Generation wire impact
  - Thermal modeling of cooling system
- LANL FY 2005 Funding:
  - $430k (LANL/DOE)
  - $430k (GE in-kind)

Sustained low heat load relies on successful long-term vacuum maintenance

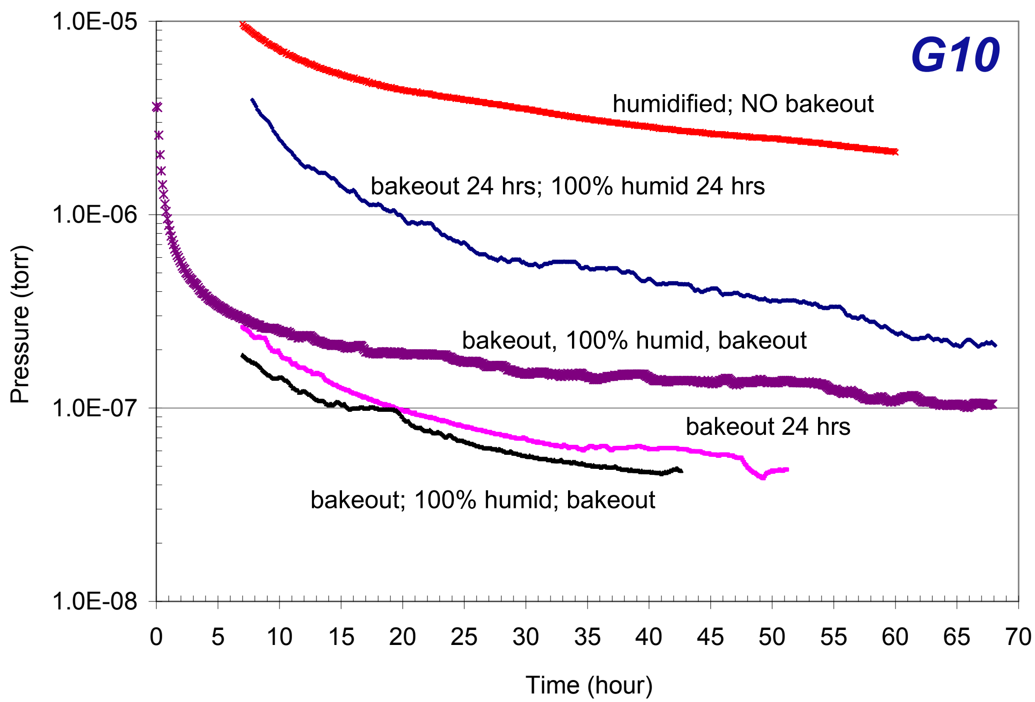
$\Downarrow$ residual gas pressure P(t) $\rightarrow \Downarrow$ *refrigeration load* $\rightarrow \Downarrow$ *refrigeration \$*

- Vacuum maintenance is a combination of two factors
  - Outgassing properties of materials used in generator
    - Gas species
    - Quantity of each species versus time
  - Getter material sizing
    - maintains low pressure by absorbing gas species
    - Has limited capacity



Data allows GE to make more reliable getter life and heat load estimates

- Alternatives to G10 (Rulon and Ultem)
- Humidified G10 samples
  - More representative of assembly environment
  - Simulate actual assembly process of generator
  - Effect of subsequent exposures to atm



Material	True outgassing rate (Torr-liter/cm^2-sec)
aluminum sheet	3.40E-09
stainless steel sheet	6.00E-10
G-10 sheet	7.00E-07
silver plated stainless	2.00E-08
aluminized mylar	5.00E-08
brush plated SS sheet	7.00E-09
soft iron	2.00E-09
Rulon	4.00E-07
Ultem	8.00E-07
Carbon fiber reinforced	1.00E-07
G-10 baked 150°F 24 hr	6.00E-08
G-10 twice humidified, and baked 150°F 24 hr	3.80E-08

this FY

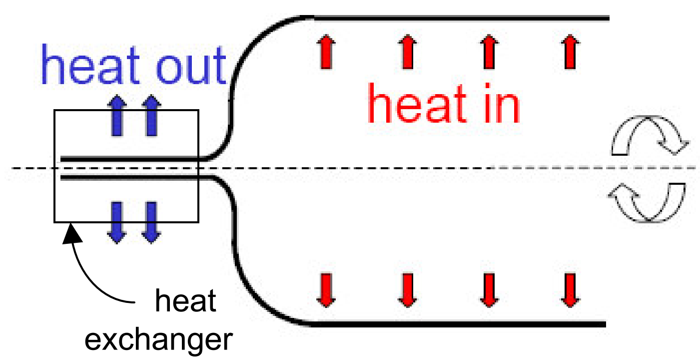
>100 total samples run;

data provided to ORNL in conjunction with emissivity work

Heat pipe integration offers high payoff rotor cooling alternative

$\Downarrow$ dT $\rightarrow$ $\Uparrow$ efficiency $\rightarrow$ $\Downarrow$ refrigeration \$

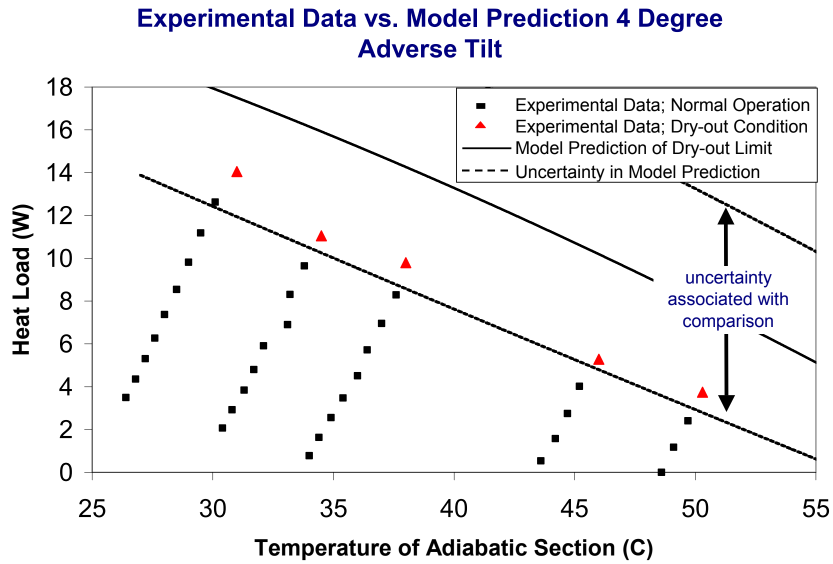
- Heat pipe has a two-phase fluid making device nearly isothermal
  - Smaller temperature difference (dT) between rotor and coupling
  - Reduced temperature gradient of rotor
  - Increases efficiency => reduces refrigeration cost
- Other advantages:
  - Sealed device that is simple and operates passively
  - Redundant cooling possibility



First 2 phases of heat pipe development are complete

1. Develop thermal-fluid heat pipe model
- Full Navier-Stokes Equ. model
- Presented at 2004 ASME Heat Transfer Conference
- After peer review, this FY model was augmented to include optimal fluid fill calculation

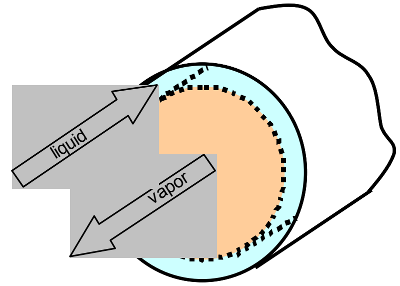
2. Fabricate heat pipe and benchmark model with stationary experimental results
- Favorable comparisons of experimental results to model
- Model continues to predict promising results for HTS rotor

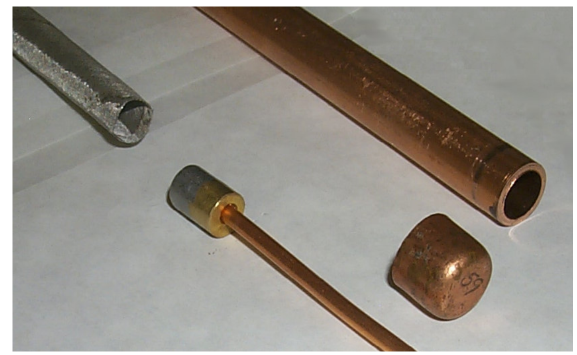


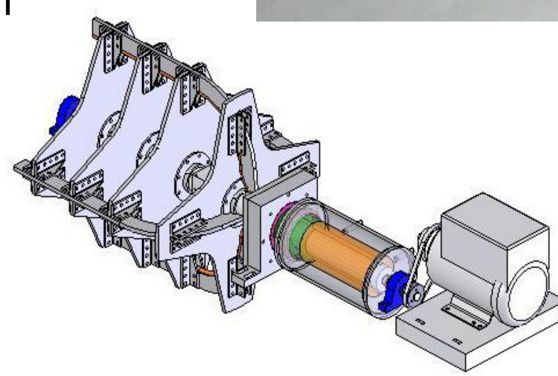
~1.5 K (~40%) reduction in dT

Preparations for rotating experiment are complete

- Heat pipe design required wick structure that enables two operation modes
  - Stationary during cooldown (annulus full)
  - High RPM during operation (annulus partially full)
- Dual-mode wick fabrication and bending was technically challenging
  - Several design iterations were fabricated and tested
  - Reliable and repeatable fabrication method determined
- Extensive safety review and authorization for a 3600 RPM test plan
- Ready for the final step of development; rotating test

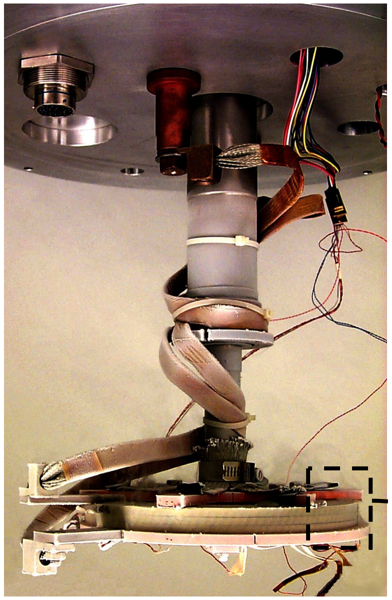


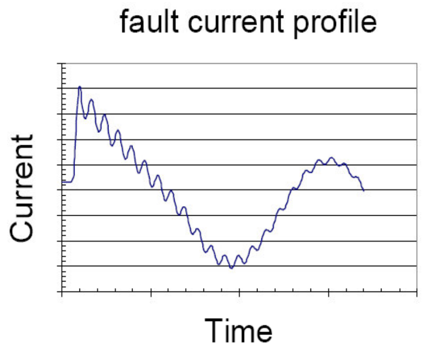




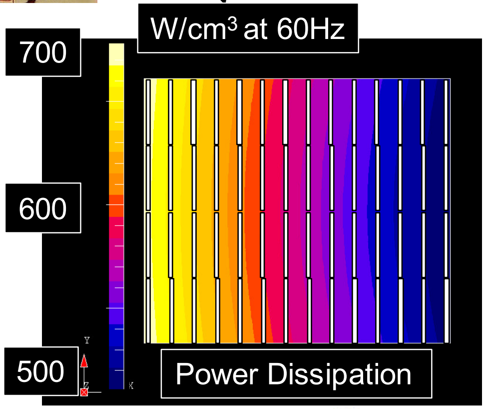
AC Loss characterization allows GE to make reliable heat load calculations

- AC fields $\Rightarrow$ joule heating
  - Increased heat load on refrigeration system during normal operation
  - In Fault Current (FC) condition $\Rightarrow$ quench magnet $\Rightarrow$ damage magnet, loss of capability
- Experiment was fabricated to determine the fault current response of the HTS coil and validate the modeling
  - 5” coil and FC profile were provided by GE
  - Coil was modeled using FEA
  - Preliminary tests were performed, identifying various hardware obstacles that we have overcome
  - Measurements are scheduled before the end of FY 2005





ID 127mm
OD 160mm
279 turns in 4 layers
Ic=150A at 30K



Los Alamos

Transient thermal modeling provides operational information

- LANL is assisting GE with steady state analysis of rotor cooling and baseline refrigeration system
  - Exchange of models
  - Review of results
- LANL is currently working with GE on parameters for transient model that we are developing
  - Capability that refrigeration system vendor does not typically have
  - Provide GE with information about thermal stresses and time/cost associated with startup/shutdown

FY 2005 Performance - 1

Plan

Extend CRADA to cover new scope

Outgassing material characterization;

- Measure additional materials as needed
- Emissivity coordination
- Document results

Rotating heat pipe experiment;

- Assemble apparatus
- Acquire data
- Compare to model
- Document results

Performance

✓CRADA extended 2 years with GE

✓Outgassing material characterization;

- [x] Measured alternative materials & assembly specific conditions
- [x] Exchanged reports with ORNL
- [x] Reports sent

Rotating heat pipe experiment *in progress*;

- [x] Heat pipe design and fabrication complete; safety analysis and authorization complete
- [ ] Stationary test data acquired; ready for rotation test plan
- [ ] Model updated and underwent peer review; stationary results match model results
- [ ] Awaiting rotation data comparison

FY 2005 Performance - 2

Plan

Passively pumped cooling experiment

- Modify rotating apparatus; fabricate/integrate loop
- Acquire data
- Compare to model
- Document results

AC Loss/Over Current

- Repair experiment
- Acquire data
- Compare to model
- Document results

Performance

Passively pumped cooling experiment

- [x] Preparation of experiment complete
- [ ] deferred testing until higher priority heat pipe test complete

AC Loss/Over Current *in progress*

- [x] Sensor connections repaired; He compressor issue identified
- [ ] Cool down underway, experiment commissioning in progress
- [ ] Modeling performed on 5” coil; model revised
- [ ] Preliminary report in progress

FY 2005 Performance - 3

Plan

2nd Generation Conductor Impact

- Assess impact
- Document results

Thermal Modeling of Refrigeration and Cooling System

(new task added to CRADA)

- Assist with baseline system development; steady state analysis as needed
- Develop transient model of system and document model

Performance

2nd Generation Conductor Impact *in progress*

- [x] Preliminary assessment was preformed and key issues identified
- [ ] Lower priority task; final assessment deferred until design is finalized and more conductor results are available

Thermal Modeling of Refrigeration and Cooling System *in progress*

- [x] Assisted with baseline system steady state analysis; models exchanged; work is ongoing
- [ ] Determination of transient model parameters and inputs in progress

FY2006 Plans

Specific CRADA deliverables will be completed in support of overall generator thermal management:

- Complete rotating heat pipe experiment
  - Run experiment at appropriate RPM, compare model, write report
- Perform passively pumped experiment
  - Run experiment at appropriate RPM, compare model, write report
- Complete AC Loss/Fault Current experiment
  - Run experiment, compare model, write report
- Complete 2nd Generation Conductor impact
  - Submit report once final design is complete
- Thermal modeling of Refrigeration and Cooling System
  - Assist GE with Reverse-Brayton cycle development as needed
  - Develop transient model, send documentation and code

Research Integration

- Interaction between GE and LANL
  - reports and teleconferencing to review direction, efforts, and results
- Exchange of software models with GE to transfer the expertise and capabilities associated with them
  - Understanding AC loss is critical for all electrical rotating machines across complex
- Interaction and exchange of results with ORNL to coordinate outgassing and emissivity efforts
- Interaction with LANL experts across organization and discipline boundaries (applied engineering ⇔ material science)
- Interaction with Prof. Razani of University of New Mexico on heat pipe development
  - Joint conference and journal papers
  - Heat pipe research serving as basis for Ph.D. dissertation
- Rotating heat pipe development advances the "state of the art"
  - Other HTS applications including motors and other rotating machinery
  - Patent pending with disclosure available for licensing

Results

LANL goals augment the HTS generator program
→ cost reduction in 2nd generation and production units:

- Enhance long term vacuum maintenance to reduce refrigeration cost
  - Completed new samples that evaluate alternative materials and operational effects
- Develop more efficient cooling system to reduce refrigeration cost
  - Completed bench testing and fabrication of heat pipe design
  - Ready to begin final phase of test plan
- Characterize AC Losses to improve thermal design margin
  - Performed modeling of test coil; hardware obstacles overcome; beginning test
- Provide expertise and thermal modeling of cooling system
  - Assisted with steady state modeling; transient model in progress